OPTIMAL DESIGN OF EXPLOSION CONTAINMENT VESSELS

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Abstract

This paper presents an optimal design concept for containment vessels that need to withstand repeated internal explosions. The concept is optimal in the sense that it gives a solution which requires the minimum strength of the vessel wall. Inmany eases, this concept does not give practical solutions, but it may be used in situations when relatively heavy fragment shields are to be used anyway.

Introduction

Explosion containment buildings and vessels that are used for the testing of explosives and munitions are heavy, expensive structures.

Their main design load is the blast from the explosions. This blast consists of a shock wave, followed by a few reflected shock waves. These shocks decay and a quasi-static pressure remains. This load can be approximated by an impulse, followed by the quasi-static pressure. In most eases the impulse is the most severe load. In many explosion containment buildings, the impulse is absorbed in thick, heavy walls. The large target room at our laboratory for ballistic research, which can withsand and explosion of 25 kg TNT, is an example of this principle. ft consists of a reinforced concrete cylinder. The concrete is not designed to take any forces, it is only there to addmass [Mercx, 1989; Mercx and Van Wees, 1991].

An interesting question is whether there is an optimal design for such a structure. This paper describes one solution for an optimal design. It starts from the idea that strength (steel) is expensive, but mass (concrete) is cheap.

It is already known that a spherical vessel is the (theoretically) optimal shape [Mercx, 1989].

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Theory

Concept

The concept that is explored in this paper is shown in Figure I. Inside the vessel wall is a heavy layer which is supported on the wall by a layer of springs. For example, this could consist of a steel shell and concrete blocks that are supported on air springs.

The impulse from the explosion gives the heavy layer a velocity, and it starts to compress the springs. After some time, the maxiinum deflection is reached and the vessel wall is loaded maximally. In the second phase, the springs are statically compressed by the quasi-static pressure. Theoretically, the load on the wall from the dynamic deflection can be manipulated at will by choosing a suitable spring stiffiiess and thickness of the heavy layer. This is not the case for the quasi-static load. Therefore, if the spring stiffhess is chosen in such a way that the dynamic load on the wall equals the quasi-static load, then the minimum strength is required for the vessel wall.

Figure 1
sketch of the design concepL A pressure vessel has a heavy internal layer, which is supported on the vessel wall by springs (in this example air springs)

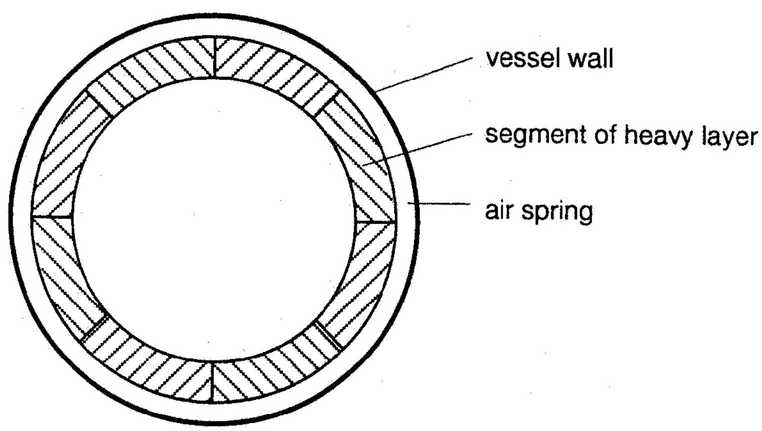

Figure 1 *Sketch of the design concept. A pressure vessel has a heavy internal layer, which is supported on the vessel wall by springs (in this example air springs)*

Mathematical elaboration

The velocity that the heavy layer gets after the impulse from the explosion is:

EQUATION

$$v = \frac{i}{\rho \cdot t} \tag{1}$$

where:

v	velocity of the heavy layer	[m/s]
i	impulse per unit area on the heavy layer	[Pa s/m^2]
ρ	density of the heavy layer	[kg/m^3]
t	thickness of the heavy layer	[m]

The kinetic energy which the heavy layer obtains is then:

EQUATION

$$E_{kin} = \frac{1}{2} \cdot \frac{i^2}{\rho \cdot t} \tag{2}$$

This energy is absorbed by the spring at its maximum deflection.

EQUATION

$$E_{spr} = \frac{1}{2} \cdot k \cdot x^2 \tag{3}$$

where:

k	spring stiffness per unit area	[Pa/m]
x	maximum deflection of the springs	[m]
E_{kin}	kinetic energy of the heavy layer per unit area	[J/m^2]
E_{spr}	absorbed energy in the springs per unit area	[J/m^2]

The maximum deflection uiider the quasi-static pressure is:

EQUATION

$$x = \frac{p_{qsp}}{k} \tag{4}$$

where:

p_{qsp} the quasi-static pressure [Pa]

Substitution of (4) in equation (3) and equating (3) and (2) gives the required spring stiffhess:

EQUATION

$$k = \rho \cdot t \cdot \frac{p_{qsp}^2}{i^2} \tag{5}$$

The maximum deflection is then:

EQUATION

$$x = \frac{1}{\rho \cdot t} \cdot \frac{i^2}{p_{qsp}} \tag{6}$$

Example: spherical steel vessel for 5 kg TNT

Take, for example, a steel vessel that needs to withstand a 5 kg TNT explosion. Its internal diameter is arbitrarily taken as 1.5 m. The impulse from this explosion is about 4750 Pa s, and the quasi-static pressure is $26 \cdot 10^5$ Pa.

First a design using only a steel shell is made. The impulse of the explosion is converted into kinetic energy of the vessel wall and this must be absorbed in elastic strain energy. The kinetic energy can be calculated with equation (2), and the strain energy for a spherical vessel at maximum elastic strain is:

EQUATION

$$E_{str} = \frac{t \cdot \sigma_y}{E} \tag{7}$$

Where:

E_{str}	strain energy in the vessel wall at maximum elastic strain	[J/m^2]
t	thickness of vessel wall	[m]
σ_y	yield stress of vessel wall	[300 MPa]
E	Young's modulus of vessel wall	[200 GPa]

Equating the kinetic energy with the strain energy gives the required wall thickness:

EQUATION

$$t = \sqrt{\frac{i^2 \cdot E}{2 \cdot \rho \cdot \sigma_y^2}} \tag{8}$$

where:

ρ	density of the vessel wall	[kg/m^3]

Substituting the values that were assumed for this example gives a thickness of 57 mm. The second design utilises the concept of the heavy layer. It is assumed that a 30 cm thick concrete layer is used. The internal diameter of the vessel remains the same, therefore the outer diameter increases. The theory predicts that the vessel wall only needs to withstand the quasi-static pressure. This requires only a thickness of 5 mm. The required spring stiffhess according to equation (5) is $2.5 \cdot 10^8$ Pa/m and the maximum deflection of the springs is only 1 cm.

The required amount of steel is only 506 kg, compared with 3125 kg without the heavy layer.

Is this a practicable concept?

The main objection to this concept is that while in reality the material costs to construct the mass are low, the construction costs are not. This applies for the springs as well. Thus, the complexity of the moving masses will, in most eases, make this concept impractical.

However, there may be some eases when this concept can be applied. Take, for example, a small vessel for about 0.5 kg TNT that we consider to build. This steel vessel is to be used very frequently and therefore the time it takes to open the closure should not be too long. The forces on the lid should therefore be minimal, to keep the number of bolts low. In this ease, the lid also requires protection from fragments. By attaching the thick fragment shield plate on springs to the closure lid, the force on the lid can be minin:ised.

Conclusions

The design concept for an explosion-containment vessel presented above will give the minimal load possible on the vessel wall. However, since it requires moving parts and springs, the added complexity will often make the concept impractical. In some eases, especially when already relatively heavy replaceable fragment shields are required, the concept can be beneficial.

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